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(54) **A heterodyne interferometer arrangement.**

(57) A heterodyne interferometer arrangement (1) comprises a two-frequency light source (LS), an optical reference branch (RB) for producing a reference signal, an optical measuring branch (MB), which includes an interferometer unit (IF) causing a phase rotation of the light beams in response to a length to be measured as well as a measuring transformer means arranged at the output of said interferometer unit, and a phase comparator means arranged subsequent to said reference transformer means and said measuring transformer means.

In order to minimize linearity errors, the measuring transformer means comprises first and second optoelectric measuring transformer units, which respond to light components orthogonal to each other and which are followed by two phase comparator means whose output signals represent phase differences between the first and the second measuring signal on the one hand and the refererence signal on the other, and a mean value generation circuit whose output signal represents the mean value of said first and second phase differences.

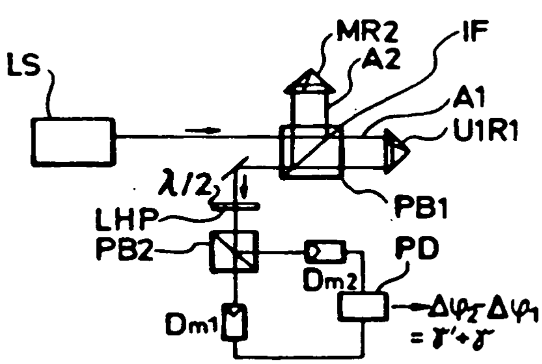

FIG. 6

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In this equation, λ_m stands for the mean wavelength. An arbitrary initial phase is $\phi_{0m} = \phi_{m1} - \phi_{m2}$.

The measuring signal I_m and the reference signal I_r are supplied to a phase comparison circuit PH, which will form the phase difference between the measuring signal I_m and the reference signal I_r.

As can be seen from equations (1c), (2a) and (2b), the measuring signal I_m is subjected to a phase displacement in comparison with the reference signal I_r, said phase displacement changing in response to changes in the optical path lengths n_1, l_1 and n_2, l_2 in the first and second arms A1, A2 of the interferometer unit IF. Hence, a length variation in one of the two arms A1, A2 can be detected by measuring a resultant phase difference between I_m and I_r.

If, in the case of one example, the resolution which can be achieved when carrying out a phase measurement is 1°, a length resolution of 0.9 nm can be attained for the detection of the displacement of a mirror MR1 and MR2, respectively, in the case of the interferometer shown in Fig. 18. The above-described phase displacement $\Delta\phi$ between the reference signal I_r and the measuring signal I_m is shown in Fig. 19. Fig. 20 shows the above-described orthogonal direction of the two partial beams E_1, E_2 as well as the arrangement of the polarization filters PF1, PF2 which are displaced by 45° relative thereto.

However, the above-described derivation of the connection between the phase displacement $\Delta\phi$ and a length L_1, L_2 to be measured is only applicable under the ideal condition that only one of the two frequencies f_1, f_2 occurs in each interferometer arm A1, A2. This ideal condition is, however, not met in practice. Due to various influences, mixed frequencies are found in both interferometer arms A1, A2. The causes of such frequency mixtures are, for example, non-orthogonality of the polarization directions M_1, M_2 of the incident waves E_1, E_2, mixing due to elliptic polarization of the incident waves E_1, E_2, mixing due to imperfect optics in the light path before the first polarizing beam splitter PB1 as well as incomplete frequency separation by said first polarizing beam splitter PB1.

These mistakes result in a non-linear relation between the measured phase difference and the displacement to be measured or the change in the optical length of one of the two interferometer arms to be measured.

The following literature sources are cited with regard to the technological background of the present invention:

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- Quenelle, R.C.; Wuerz, L.J.:
  A new micrometer-controlled laser dimensional measurement and analysis system.
  Hewlett Packard Journ. 34,4 (1983), 3 - 13
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  Hochauflösende Interferometrie mit Zweifrequenzlasern PTB-Mitt. 90, (1980), 359 - 362
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  PTB-Mitt. 93, (1983), 168 - 174
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  Residual errors in laser interferometry from air turbulence and nonlinearity
  Appl. Opt. 26, (1987), 2676 - 2682
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  Non-linearity in length measurement using heterodyne laser Michelson interferometry
  J. Phys. E 20, (1987), 1290 - 1292
- Steinmetz, C.R.:
  Sub-micron position measurement and control on precision machine tools with laser interferometry
  Prec. Eng. 12, (1990), 12 - 24
- Rosenbluth, A.E.; Bobroff N.:
  Optical sources of non-linearity in heterodyne interferometers
  Prec. Eng. 12, (1990), 7 - 11

Taking this prior art as a basis, the present invention is, in accordance with a first aspect of the invention, based on the object of further developing a heterodyne interferometer arrangement as well as a heterodyne interferometric metering technique of the type mentioned at the beginning in such a way that the measuring error of linearity is reduced.

This object is achieved by a heterodyne interferometer arrangement according to patent claim 1 and by a heterodyne interferometric metering technique according to patent claim 5.

In view of the fact that, in the case of known heterodyne interferometer arrangements and in the case of known heterodyne interferometric metering techniques, linearity errors will occur - as has already been

The following relation then results for the measuring signal I_m, which corresponds to the a.c. output signal of the measuring photodiode D_m:

(3c) $I_m \sim A^* I_0 \cos[2\pi(f_1 - f_2)t + \phi_{0m} + \Delta\phi - \gamma]$

$$(4) \quad \gamma = tg^{-1} \frac{\sin\alpha \sin\Delta\varphi}{\cos\alpha + \sin\alpha\cos\Delta\varphi}$$

(5) $A^* = \sqrt{1 + \sin 2\alpha \cos\Delta\phi}$

On condition that α is much smaller than 1 - said condition being fulfilled in the case of the relation $\alpha < 5°$ - the systematic phase error γ can be expressed by the following equation in first approximation.

(6) $\gamma \simeq \alpha \sin\Delta\phi$

A comparison between equations (2b) and (3c) shows that the phase measurement carried out by means of the known interferometer arrangement shown in Fig. 18 is affected by a systematic error γ, said systematic error γ being a periodic error which varies with the phase difference $\Delta\phi$. The maximum error is 2α. If $\alpha = 5°$, for example, the maximum error of phase measurement will be 10°. This corresponds to an error of 9 nm in the length measurement in the case of the heterodyne interferometer according to the prior art which has been described at the beginning.

It should also be noted that the amplitude of the measuring signal I_m is no longer constant in contrast to the ideal case (cf. equation (2a)), but represents a periodic signal modulated by α and $\Delta\phi$ (cf. equation (5)).

Also the other causes of failure, which have been mentioned at the beginning and in view of which mixing occurs, cause similar results. When there is frequency mixing in both arms, the phase errors behave additively. But a simple rotation of the polarization directions of the incident light wave relative to those of the interferometer theoretically do not cause first order phase errors.

Mixing errors due to leakage of the first polarizing beam splitter PB1 can mostly be neglected, because the leakage flux retains its polarization and must pass the first polarizing beam splitter PB1 at least once more before mixing of the leakage flux can take place at the location of the receiver. The first polarizing beam splitter PB1 normally has a rejection ratio of 0.3 % in intensity. The resulting phase error leads to a maximum error in the length measurement of 0.17 nm in the case of the heterodyne interferometer arrangement shown in Fig. 18 and 0.001 nm for differential interferometers.

Non-ideal non-polarizing or polarizing optics behind the first polarizing beam splitter PB1 do not cause the error of non-linearity.

In the case of the heterodyne interferometric metering technique according to the present invention, two measuring signals I_{m1} and I_{m2} are produced, which represent light components orthogonal to each other at the output of the interferometer unit. The following equations are obtained for the two measuring signals:

(7) $I_{m1} = I_m \sim A^* I_0 \cos[2\alpha(f_1 - f_2)t + \phi_{0m} + \Delta\phi - \gamma]$

(8) $I_{m2} \sim -B^* I_0 \cos[2\pi(f_1 - f_2)t + \phi_{0m} + \Delta\phi + \gamma']$

The negative sign in equation (8) for the second measuring signal I_{m2} corresponds to a constant phase displacement of π relative to the first measuring signal I_{m1}, and that has no influence on phase measurement. In the eighth equation, the following relationships exist:

(9) $B^* = \sqrt{1 - \sin 2\alpha \cos\Delta\phi}$

photodiodes. The output signals of these measuring transformer units are supplied to a phase difference circuit PD, which will form the phase difference as defined in equations 14 and 15.

In the following, the residual error occurring in the case of the heterodyne interferometric metering technique according to the present invention is to be determined. It can be obtained from equations 12 and 13:

(16) $(\Delta\phi_1 + \Delta\phi_2)/2 = \Delta\varphi + \epsilon$

and (17) $\epsilon = (\gamma' - \gamma)/2$

$$= \frac{1}{2}\sin^{-1}\frac{\sin^2\alpha\sin(2\Delta\varphi)}{\sqrt{1-\sin^2(2\alpha)\cos^2(\Delta\varphi)}}$$

$$\simeq \frac{1}{2}\alpha^2\sin(2\Delta\varphi) \qquad (\text{if } \alpha \ll 1)$$

As can be seen in Fig. 8, the residual error ϵ is mostly negligible so that the measured value obtained by forming the mean value of the phase differences in the case of the interferometric metering technique according to the present invention is virtually free from non-linearity.

It is, however, emphasized that in the case of the heterodyne interferometric metering technique according to the invention, the two measuring signals I_{m1}, I_{m2} cannot directly be related with each other for forming the mean value of the phases, because the amplitudes of these measuring signals are no longer constant and have opposite phases so that an error would be caused if a simple phase addition were carried out. As has already been mentioned, it will be necessary to compare the two orthogonal measuring signals I_{m1}, I_{m2} separately with the reference signal I_r and then form the arithmetic mean value of the resultant phase differences.

A heterodyne interferometer arrangement suitable for carrying out the heterodyne interferometric metering technique according to the invention is shown in Fig. 9.

As far as the arrangement according to Fig. 9 corresponds to the arrangement according to the prior art according to Fig. 18, which has already been explained, identical or similar parts will be provided with identical reference numerals so that a renewed explanation of these components can be dispensed with.

In the case of the heterodyne interferometer arrangement according to the present invention, the output of the interferometer unit has connected thereto a receiver unit RU, which generally divides the emergent light into two orthogonal light components and which supplies these components to first and second optoelectric measuring transformer units D_{m1}, D_{m2} so as to produce first and second measuring signals I_{m1}, I_{m2}, respectively; said optoelectric measuring transformer units may be constructed as photodiodes. The output signals of these measuring transformer units D_{m1}, D_{m2} are supplied to first and second phase comparator units PH1, PH2 whose reference input has applied thereto the reference signal I_r. The resultant two phase difference signals $\Delta\phi_1$, $\Delta\phi_2$ at the respective outputs of the phase comparator units PH1, PH2 are supplied to a mean value generation circuit MV, which will form the arithmetic mean value of the two phase differences.

The receiver unit for a heterodyne interferometer arrangement according to the invention can be realized in different ways. Three possible embodiments are shown in Fig. 10, 11 and 12.

A feature which is common to all embodiments of this receiver unit RU is that the light wave coming from the output of the interferometer unit IF is subdivided into two light components, which are orthogonal to each other and which are supplied to first and second optoelectric measuring transformer units D_{m1}, D_{m2}.

The structural design of the receiver unit according to Fig. 10 corresponds to the relevant arrangement of Fig. 9. It should also be noted that, in the case of the structural design of Fig. 10, the second polarizing

and which is provided with a reference transformer means (D_r) for producing a reference signal;
- an optical measuring branch (MB), which has supplied thereto a part of said light beams (E_1, E_2) and which includes an interferometer unit (IF) causing a phase rotation of said light beams (E_1, E_2) in response to a length to be measured as well as a measuring transformer means arranged at the output of said interferometer unit (IF); and
- a phase comparator means arranged subsequent to said reference transformer means and said measuring transformer means,

characterized in
- that the measuring transformer means comprises first and second optoelectric measuring transformer units (D_{m1}, D_{m2}) responding to light components which are orthogonal to each other so as to produce first and second measuring signals (I_{m1}, I_{m2}); and
- that the phase comparator means comprises first and second phase comparator units (PH1, PH2) whose output signals represent first and second phase differences ($\Delta\phi_1$, $\Delta\phi_2$) between the first or second measuring signal (I_{m1}, I_{m2}) on the one hand and the reference signal (I_r) on the other, and a mean value generation circuit (MV) which is arranged subsequent to said phase comparator units (PH1, PH2) and the output signal of which represents the mean value of said first and second phase differences.

2. A heterodyne interferometer arrangement according to claim 1, **characterized in**

that the measuring transformer means is provided with a polarization direction rotating means (LHP) arranged at the output of the interferometer unit and with a polarizing beam splitter means (PB2) supplying the orthogonal light components to the measuring transformer units (D_{m1},D_{m2}), and

that the polarization direction of the polarizing beam splitter means (PB2) corresponds to the direction of one of the two light components.

3. A heterodyne interferometer arrangement according to claim 1, **characterized in**

that the measuring transformer means is provided with a polarizing beam splitter means (PB2), which is arranged at the output of the interferometer unit (IF) and the polarization direction of which is rotated by 45° relative to the direction of the orthogonal light components, said polarizing beam splitter means supplying the orthogonal light components to the measuring transformer units (D_{m1}, D_{m2}).

4. A heterodyne interferometer arrangement according to claim 1, **characterized in**

that the measuring transformer means comprises a non-polarizing beam splitter means (NPB2) arranged at the output of the interferometer unit (IF) and two polarization filters (PF3, PF4) which are displaced by 90° relative to each other with regard to their polarization directions and which are used for filtering out the orthogonal light components supplied to the measuring transformer means (D_{m1}, D_{m2}).

5. A heterodyne interferometric metering technique comprising the following steps:
- producing a reference signal (I_r) representing a reference phase (ϕ_0) of the light beams (E_1, E_2) at the input of an interferometer unit (IF);
- rotating the phase of the light beams (E_1, E_2) in said interferometer unit (IF) in response to a length to be measured;
- producing a measuring signal representing the phase of the light beams at the output of the interferometer unit (IF); and
- comparing the phase of the reference signal (I_r) and of the measuring signal so as to produce a phase difference ($\Delta\phi$) which depends on the length to be measured;

characterized in
- that the step of producing a measuring signal comprises the production of first and second measuring signals (I_{m1}, I_{m2}) representing light components which are orthogonal to each other at the output of the interferometer unit (IF); and
- that the step of comparing the phases comprises the production of first and second phase differences ($\Delta\phi_1$, $\Delta\phi_2$) between the first or second measuring signal (I_{m1}, I_{m2}) on the one hand and the reference signal (I_r) on the other as well as the generation of a mean value of the two

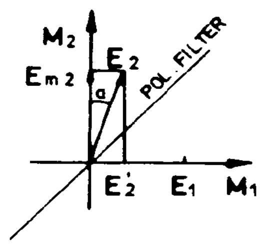


FIG.1

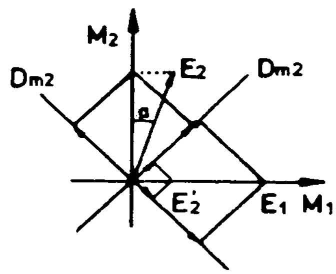
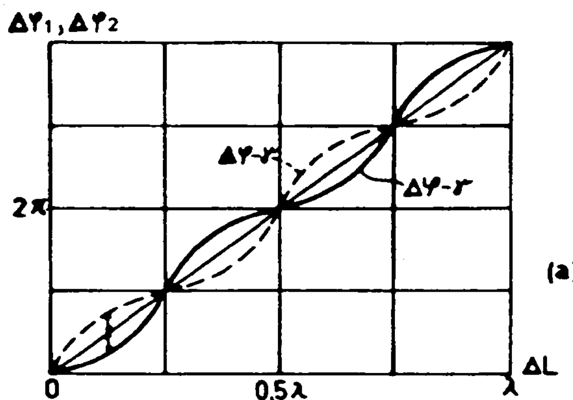
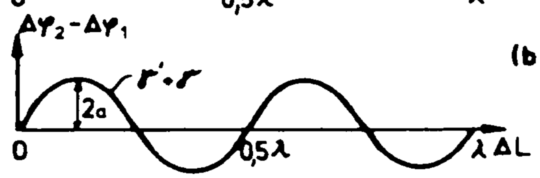


FIG. 2



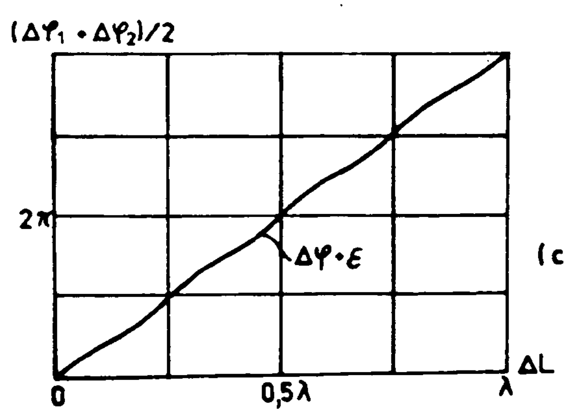
(a)

FIG.3



(b)

FIG.4



(c)

FIG.5

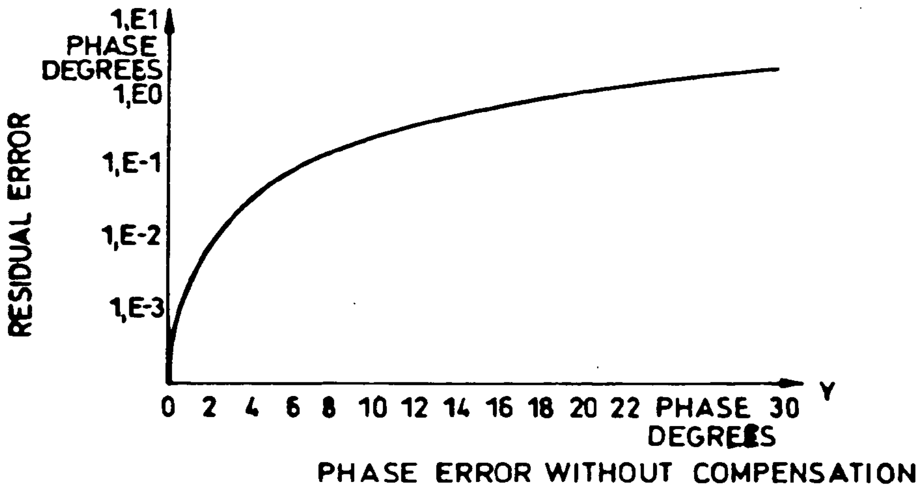


FIG.8

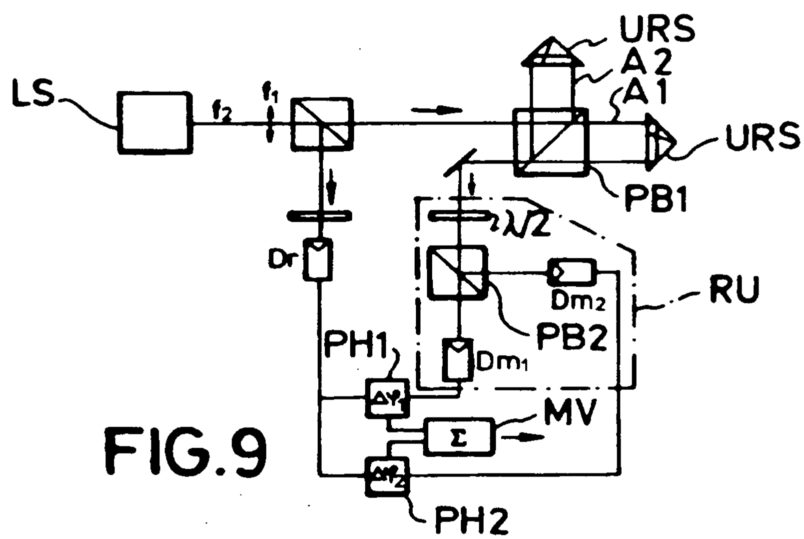


FIG.9

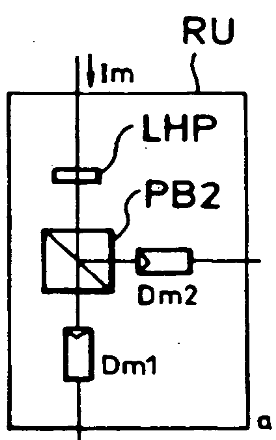


FIG.10

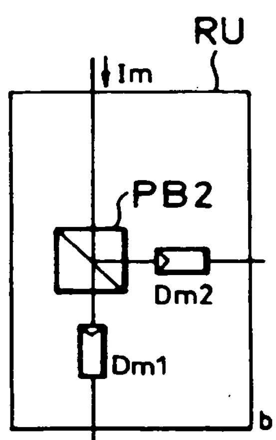


FIG.11

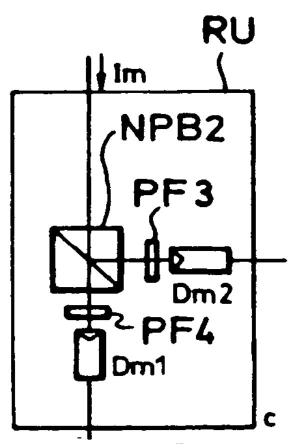
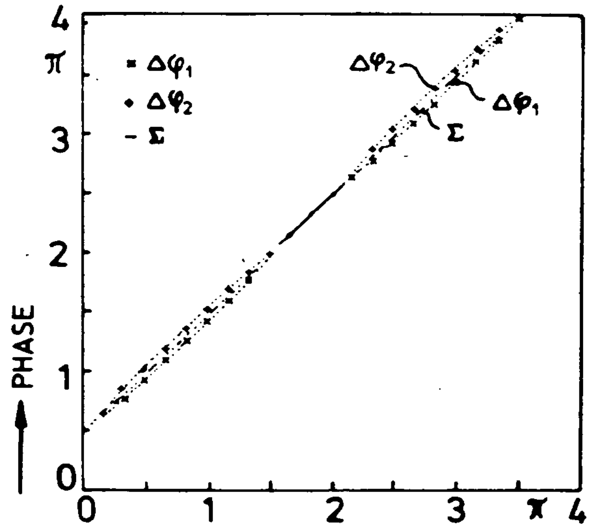
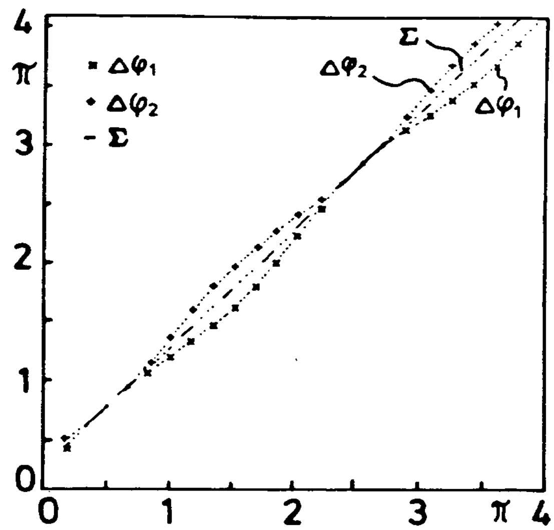


FIG.12



a1

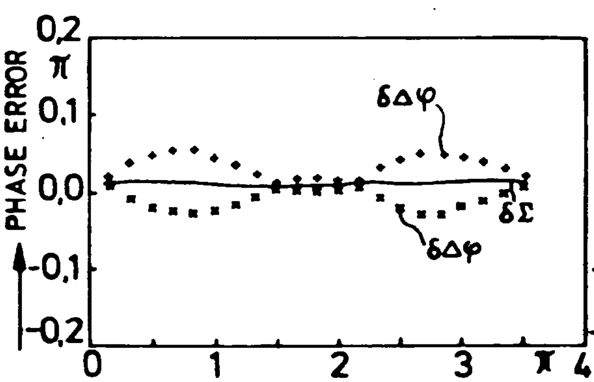
FIG.14



b1

FIG.16

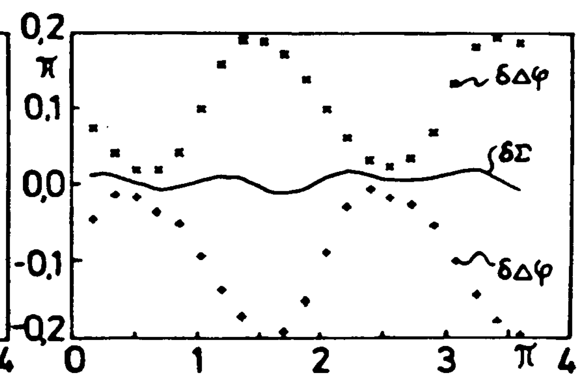
$\Delta\varphi$



$(\delta\Delta\varphi_1)_{max}$ = 8,5° (7.7 nm)
$(\delta\Delta\varphi_2)_{max}$ = 9,6° (8,6 nm)
$(\delta\Sigma)_{max}$ = 1,3° (1,2 nm)

a2

FIG.15



$(\delta\Delta\varphi_1)_{max}$ = 31,2° (27,1 nm)
$(\delta\Delta\varphi_2)_{max}$ = 34,0° (29,6 nm)
$(\delta\Sigma)_{max}$ = 5,1° (4,4 nm)

b2

FIG.17

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 91 10 8444

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
A	PRECISION ENGINEERING vol. 12, no. 1, 1 January 1990, pages 7 - 11; A. ROSENBLUTH ET AL.: 'OPTICAL SOURCES OF NON-LINEARITY' * page 7 - page 10 *	1,5-7	G01J9/04 G01B9/02
A	JOURNAL OF VACUUM SCIENCE & TECHNOLOGY B vol. 8, no. 6, 1 December 1990, NEW YORK pages 2032 - 2036; W. AUGUSTYN: 'AN ANALYSIS OF POLARIZATION MIXING ERRORS' * page 2034 - page 2036 *	1,5	
A	JOURNAL OF PHYSICS E: SCIENTIFIC INSTRUMENTS vol. 20, no. 10, 1 October 1987, pages 1290 - 1292; C. SUTTON: 'NON-LINEARITY IN LENGTH MEASUREMENT' * page 1290 - page 1292 *	1,5-7	
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A	US-A-4 948 251 (M. KONDO) 14 August 1990 * column 5 - column 11 *	1	
A	PATENT ABSTRACTS OF JAPAN vol. 12, no. 319 (P-751)(3166) 30 August 1988 & JP-A-63 085 302 (HOYA CORP.) 15 April 1988 * abstract *	1	

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	22 JANUARY 1992	BOEHM C.E.

CATEGORY OF CITED DOCUMENTS

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